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BETA-DELAYED FISSION CALCULATIONS FOR THE ASTROPHYSICAL r-PROCESS

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Abstract

We discuss RPA calculations of the Gamow-Teller properties of neutron-rich nuclei to study the effect of β-delayed fission and neutron emission on the production of Th, U and Pu chronometric nuclei in the astrophysical r-process. We find significant differences in the amount of β-delayed fission when compared with the recent calculations of Thielemann et al. (1983). In the simplest case of a constant abundance along the r-process path, however, the inferred production ratios in both calculations are similar.

The study of the decay of nuclei from the r-process path back to the β-stability line is an area of astrophysics which requires knowledge of β-strength functions off the line of beta stability. This knowledge is especially important for the determination of the abundances of the progenitors of the Th-U-Pu chronometers since β-delayed fission and neutron emission during decay back to the stability line may significantly affect the final abundance distribution of these nuclei ([BER69], [WEN75], [KOD75], [KRU81]). The β-strength function for nuclei along the decay back paths [coupled with neutron separation energies (S_n), fission barrier heights (B_f) and β-decay Q-values (Q_β)] determines the amount of β-delayed fission and neutron emission that occurs during the cascade back to the β-stability line.

A recent analysis by Thielemann et al. [THI83] of the effects of β-delayed processes on the progenitors of the Th-U-Pu chronometers showed that these processes (delayed fission in particular) did indeed significantly influence the final abundances of the chronometer progenitors. This leads to a long age for the Galaxy. In view of the importance of this result, it is useful to re-examine the calculation with a nuclear model that includes the effects of nuclear deformation on the β-decay rates, fission barriers, and neutron separation energies self-consistently.

Since many of the nuclei involved are presumably highly-deformed, we have used the Nilsson RPA code of Krumlinde and Möller [KRU84], which calculates β-strength functions, using an infinite-range residual (Gamow-Teller) interaction with a strength χ_{GT} = 23/A MeV. With this code, we have calculated β-strength functions for 118 nuclei lying in the mass range from A=232 to A=255 and from the line of β-stability to the r-process path given by Thielemann et al. [THI83] (see Fig.1). These 118 nuclei satisfied the criteria for possible β-delayed fission (Q_β of precursor $\gtrsim B_f$ of emitter) and/or possible β-delayed neutron emission (Q_β of precursor $\gtrsim S_n$ of emitter) as determined from the values given in [HOW80].

The required input values are the deformation parameters ε_2 and ε_4 and the numbers κ and μ which determine the size of the $\mathbf{l}\cdot\mathbf{s}$ force and $\mathbf{l}^2$ terms for the harmonic oscillator. We adopted the values κ_p = 0.0577 and μ_p = 0.650 for protons and κ_n = 0.0635 and μ_n = 0.325 for neutrons over the entire range studied, in accordance with [HOW80]. The values of ε_2 and ε_4 for each nucleus were taken from the same source.

From our β-strength distributions, we then calculated rates as a function of excitation energy in the daughter nucleus. These rates and the Q_β, B_f, and S_n values [HOW80] give the amount of β-delayed fission and neutron emission for each daughter nucleus. Our results are shown in Fig. 1. The numbers in the squares in Fig. 1(a) give the percentage of decays resulting in a daughter nucleus excitation energy greater than or equal to the fission barrier height. The numbers in the squares in Fig. 1(b) give the percentage of decays resulting in an daughter nucleus excitation energy greater than or equal to the neutron separation energy but less than the fission barrier height. In order to determine the maximum possible effect of delayed fission, we take the number from (a) as the amount of β-delayed fission and the number from (b) as the amount of β-delayed neutron emission in the daughter nucleus. This undoubtedly leads to an overestimate of delayed fission probabilities in some cases.

For the purpose of simple comparison with [THI83], we assume constant abundances (1.0 per isobar) along the r-process path shown in Fig.1. After β-delayed fission and neutron emission during decay back, the final abundances are those shown in Table 1. Clearly β-delayed fission plays a large role in decay back at A ≥ 250. On the other hand, β-delayed neutron emission does not affect the abundances too much, since loss from chain A is more or less compensated for by gain from chain A+1, except in a few cases (A = 234, 236, 239, 244, 248, and 249). Of course, a more significant effect of delayed neutron emission will be seen if we take more realistic initial abundances along the r-process path, which usually exhibit a strong even-odd effect.

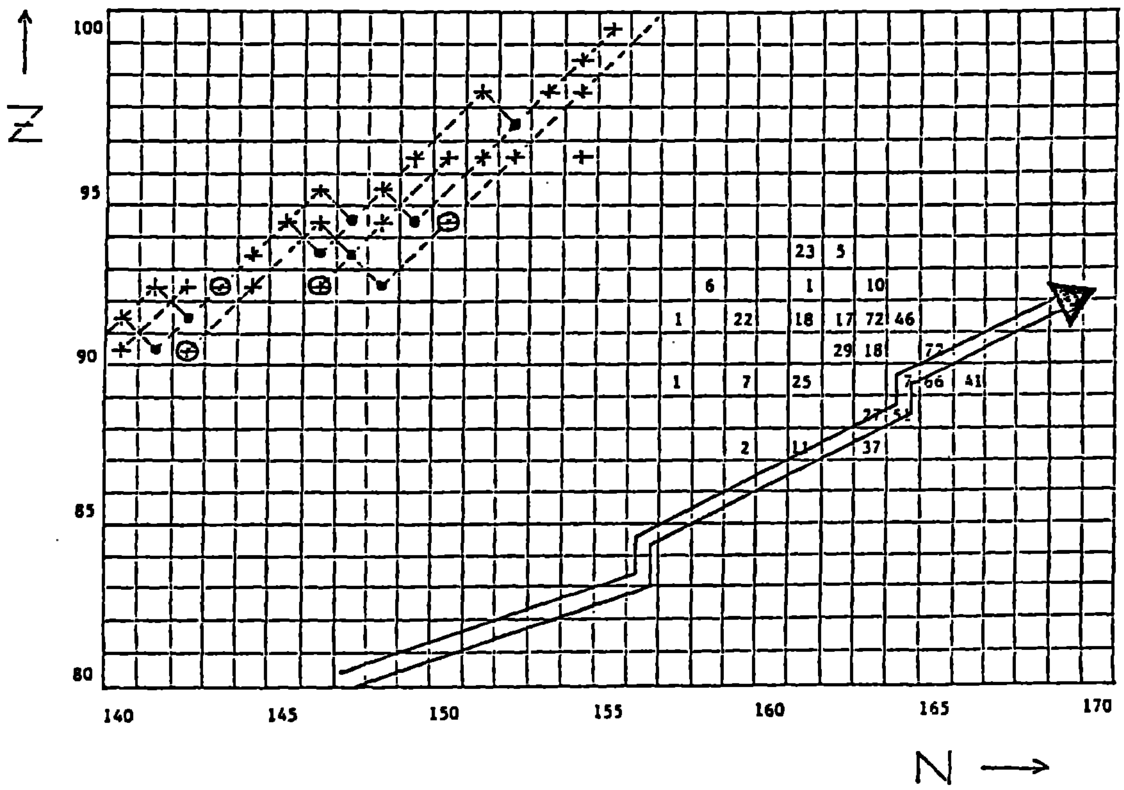

Fig. 1(a). Calculated maximum possible values of β-delayed fission probabilities (in %) shown for the precursor nuclei. The arrow follows the r-process path given in [THI83]. The crosses indicate β-stable nuclei, and the dashed lines indicate α decays. The r-process nuclear cosmo-chronometers are circled.

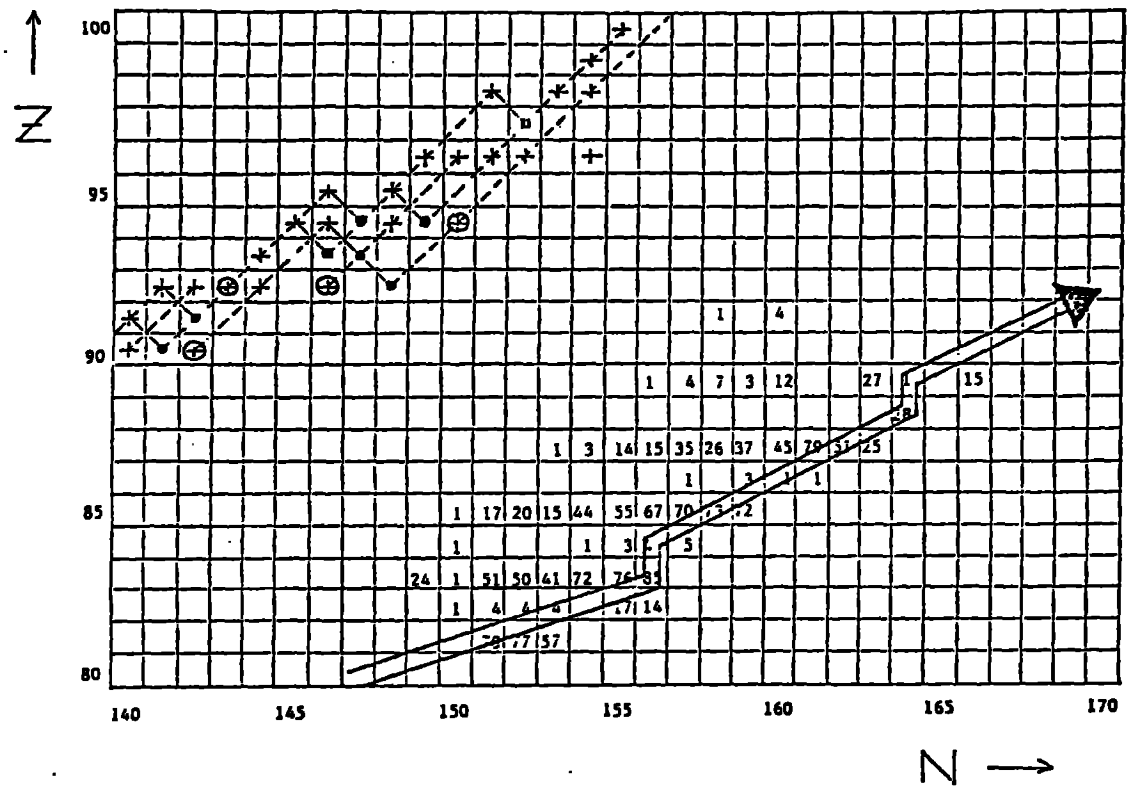

Fig. 1(b). Calculated minimum possible values of β-delayed neutron emission probabilities (in %). See the caption to Fig.1(a).

Table 1. Isobaric abundance changes during the cascade from the initial value of 100 % at the r-process path shown in Fig. 1 down to the β-stable nuclei marked by crosses.

A	%	A	%
232	78	244	47
233	102	245	112
234	70	246	110
235	118	247	124
236	133	248	64
237	92	249	64
238	97	250	47
239	67	251	32
240	115	252	67
241	111	253	18
242	103	254	11
243	94	255	6

From the results in Table 1, we can find the r-process production ratios of interest to nuclear cosmo-chronology: $^{232}Th/^{238}U$, $^{235}U/^{238}U$, and $^{244}Pu/^{238}U$. These are obtained by summing the α-decay progenitors for each isotope and considering the leak due to spontaneous fission. Our results are $^{232}Th/^{238}U = 1.60$ $^{235}U/^{238}U = 1.42$, $^{244}Pu/^{238}U = 0.57$. Our value for $^{232}Th/^{238}U$ ratio in this approximation of constant r-process abundances would imply a lower limit on the Galaxy's age of 8.8 Gyr. However, it is important to note that the final production ratios will be dependent on the explicit r-process calculation employed [FOW85]. (See also [MEY85], [THI83] and [YOK83] for further details on nuclear cosmo-chronology.)

For comparison, we give the values for the chronometer production ratios determined by Thielemann et al. [THI83] for constant abundances along the r-process path: $^{232}Th/^{238}U = 1.63$, $^{235}U/^{238}U = 1.21$, and $^{244}Pu/^{238}U = 0.13$. To our surprise, our $^{232}Th/^{238}U$ ratio agrees well with [THI83], despite the large difference between the two calculations in the amount of β-delayed fission (compare Fig. 1(a) with Fig. 2 of [THI83]). This result suggests that β-delayed processes do indeed significantly affect the abundances of the progenitors of the r-process chronometers. The other two sets of ratios differ rather strongly, however. These differences are not surprising because of the different β-strength functions and adopted mass formulae (for Q_β and S_n), although both sets of calculations used the same fission barrier heights. It is worth emphasizing that the virtue of our calculations are that all input data were taken from a single source [HOW80], i.e., the effects of nuclear deformations on the fission barriers and β-strength functions were treated self-consistently. We understand that many uncertainties still exist in this calculation and, therefore, that further work is still required. We hope to pursue this study in the near future and will be aided by improvements in the code used for calculating the β-strength functions (e.g., the inclusion of the first-forbidden decay) and in the set of Q_β, B_f and S_n values. We will also include a more realistic determination of the competition between delayed fission and delayed neutron emission. These improvements should lead to a better understanding of decay back to the β-stability line and help in the search for the astrophysical site(s) for the r-process.

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